Working principle and performance of GEM detectors

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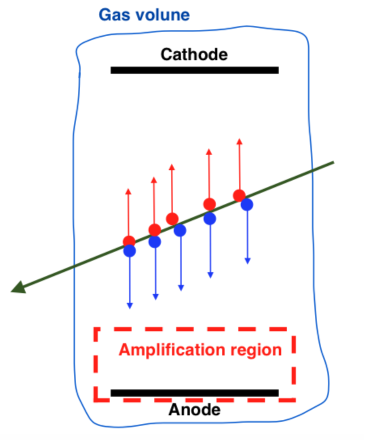
12^{th} of July, 2017

Outline

- Introduction
- Gas Electron Multipliers (GEMs)
  - Production
  - Working principle
  - Characteristics
- The COMPASS GEM tracker
- GEM Performance: Studies for the ALICE TPC Upgrade
- More detectors using GEMs
- Summary

Electron amplification in a gas mixture



Today's readout-electronics for gaseous detectors aren't sensitive to ∼single electrons

→ Primary ionisations need to be amplified

→ Increase the kinetic energy of primary electrons until they further ionise the gas

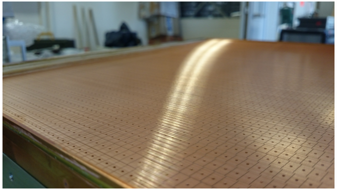
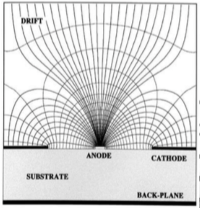
$$\epsilon_{\mathrm{eKin}} \sim \frac{\mathrm{E}}{N\sigma}\sqrt{\lambda}$$

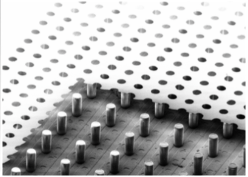
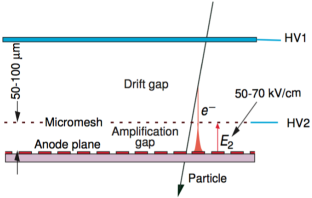
Transport the e^- into a region with high electric field to provide the electrons with enough kinetic energy to create → **electron multiplication**

Requirements on a gas amplification stage

The example of detectors used for tracking and PID detectors:

- All the primary electrons enter the amplification stage
- The amplification has a known dependence on the incoming charge
- The mechanical structure allows for the desired position resolution
- Only few (or no) ions drift back into the drift volume
- The amplification stage is stable against discharges

Gas Electron Multipliers

Nuclear Instruments and Methods in Physics Research A 386 (1997) 531–534

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

Letter to the Editor

GEM: A new concept for electron amplification in gas detectors

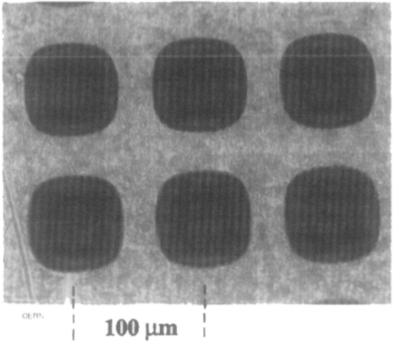
F. Sauli

CERN, CH-1211 Genève, Switzerland

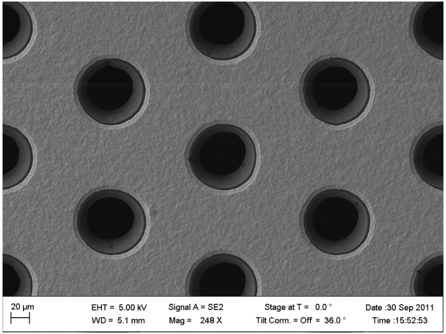
Received 6 November 1996

Abstract

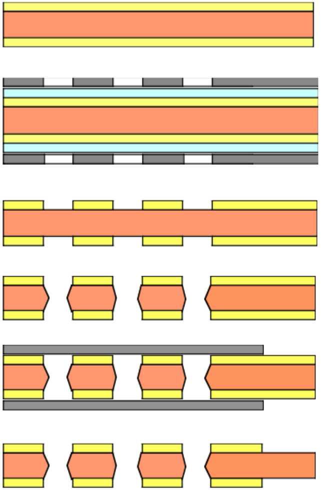
We introduce the gas electrons multiplier (GEM), a composite grid consisting of two metal layers separated by a thin insulator, etched with a regular matrix of open channels. A GEM grid with the electrodes kept at a suitable difference of potential, inserted in a gas detector on the path of drifting electrons, allows to pre-amplify the charge drifting through the channels. Coupled to other devices, multiwire or microstrip chambers, it permits to obtain higher gains, or to operate in less critical conditions. The separation of sensitive and detection volumes offers other advantages: a built-in delay, a strong suppression of photon feedback. Applications are foreseen in high rate tracking and Cherenkov Ring Imaging detectors. Multiple GEM grids assembled in the same gas volume allow to obtain large effective amplification factors in a succession of steps.



Adopted from [1].



Double-mask technique



Adopted from [2].

GEMs are produced from a 50 μm polyimide film with a layer of 5 μm copper layer on each side:

1. A photoresist is spread on both sides of the raw material
2. On both sides a mask is added, which is afterwards exposed to UV light **Double Mask technique**
3. The photoresist is developed and then the copper is etched
4. In a last step the polyimide is etched

Limitation:

The two masks have to be aligned with better than 10 μm precision:

- This limits the possible GEM size to $40 \cdot 40\,\mathrm{cm}^2$

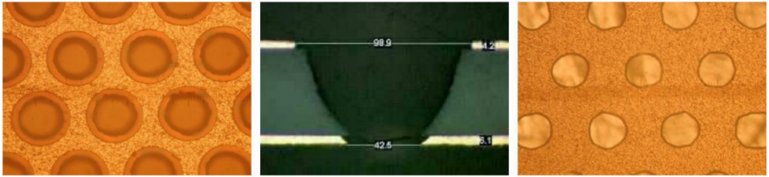
Single-mask GEMs

The process of imprinting a mask is only done on one side of the foil, while the other side is protected.

After the hole pattern is etched on this side, the polyimide is etched and afterwards again the copper.

Allows for the production of large size GEM foils

Single-mask technique



Adopted from [3].

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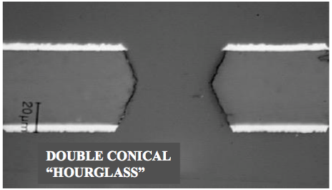

Adopted from [2].

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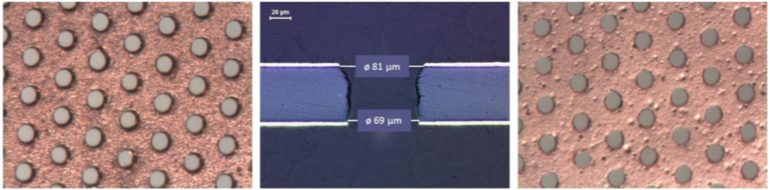
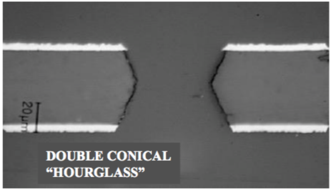


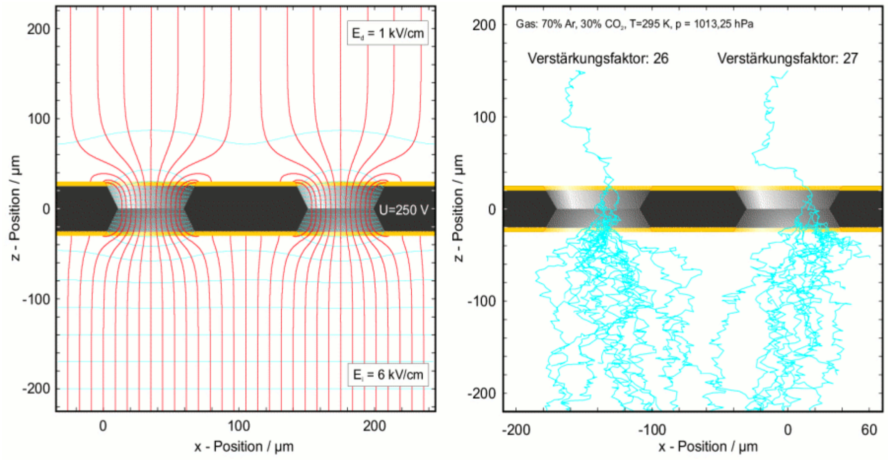
Adopted from [3].

Double-mask technique



Adopted from [2].

Working principle of a GEM foil



Adopted from [4].

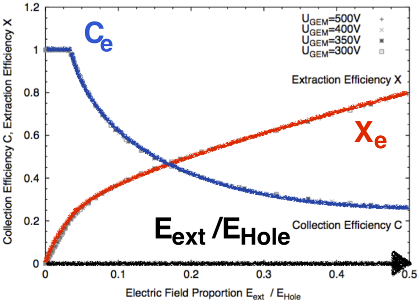
Parametrisation of the GEM performance

- Gain (G) – the multiplication factor
- Electron collection (C_e) and extraction efficiency (X_e)
- Primary ion extraction efficiency (X_{Ion})
- Secondary ion collection (C_{SecIon}) and extraction efficiency (X_{SecIon})

And derived quantities, e.g. the effective gain and the Ion Back Flow (IBF)

$$G_{\mathrm{Eff}} = N_e^{\mathrm{primary}} \cdot C_e \cdot G \cdot X_e$$

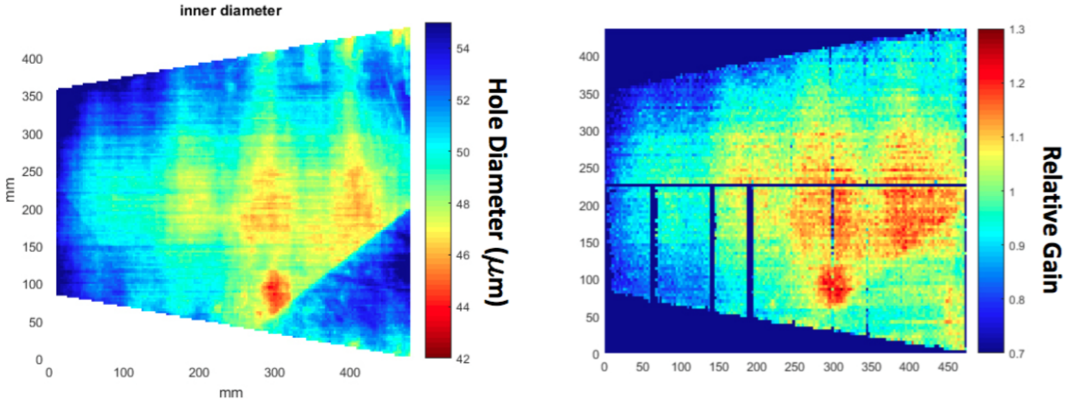
$$\mathrm{IBF} = N_e^{\mathrm{primary}} \cdot C_e \cdot G \cdot X_{\mathrm{Ion}}$$



Adopted from [5].

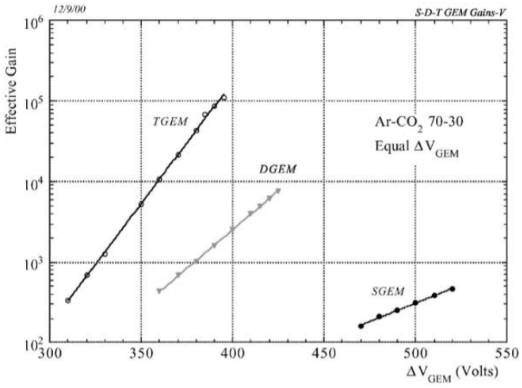
All these parameters depend either on the chosen gas, the geometry of the GEM foil and the voltage across the foil or on a combination of several of those.

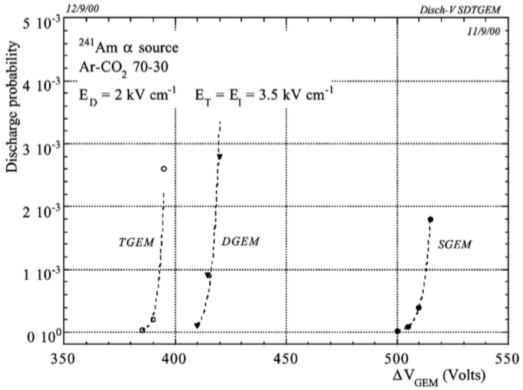
Influence of the hole geometry on the gain



Scan of the *inner hole diameter* of a GEM foil and a gain scan of this foil. (Done for the ALICE TPC Upgrade.)

Gain & discharge probability





Adopted from [6].

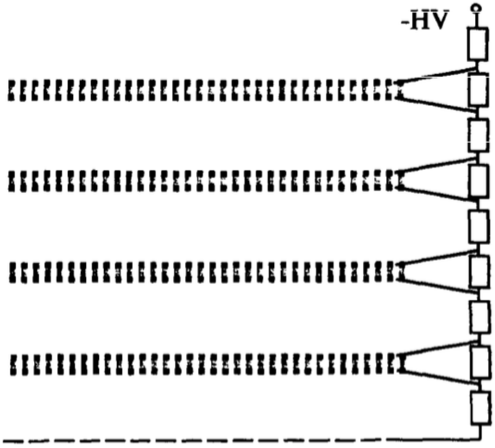
Stacking GEMs

Using several GEMs in a stack allows to:

- Split the gas gain over several GEMs
- Reduce the voltage across the two sides of the used GEM foils (as compared to an e.g. single-GEM configuration)

Thus:

- Achieving the same gain
- Reducing the probability for discharges

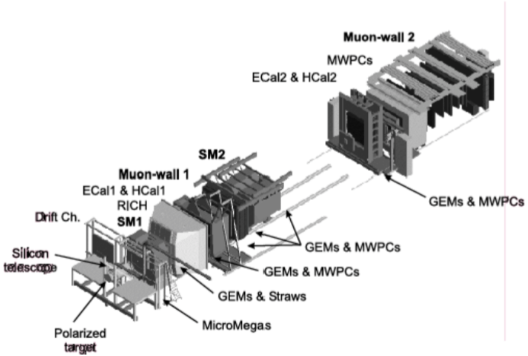


Adopted from [1].

Intermediate Summary: GEMs

- A standard GEM foils is 50 µm ployimide foil with a 5 µm copper layer on each side and a hexagonal hole pattern with a pitch of 140 µm
- If a sufficient voltage difference is applied between the copper sides of a GEM foil, a high electric fields is present in the GEM holes allowing for electron multiplication
- The effective gain of a GEM depends on the electric fields in the holes, their geometry and the field below/above the foil
- While using stacks of several GEMs, high gains can be achieved, while having a low discharge probability

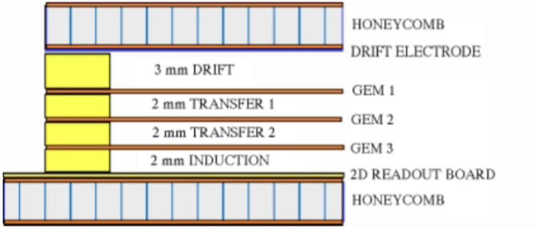
Large experiment to use GEMs: COMPASS



Adopted from [10].

COMPASS: GEM based tracking chambers

- Start of data taking: 2002
- Fixed target experiment
- $\sim 10^8$ particles impinging on a target per $\sim 5\,\text{s}$ spill

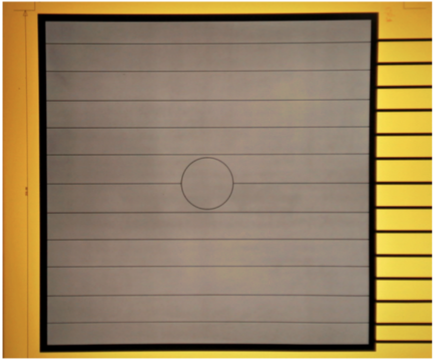


Adopted from [10].

- 20 readout chambers with a triple GEM stack used in the near beam area
- Particle fluxes up to $25\,\text{kHz}\,\text{mm}^{-1}$
- The COMPASS GEM chambers are not operated in a TPC mode, but as 'classical' tracking stations.
- $31 \cdot 31\,\text{cm}^2$ standard GEMs
- Strip readout with orthogonal X and Y strips (400 µm pitch)
- Spatial resolution around 70 µm [11]
- Time resolution around 12 ns [11]

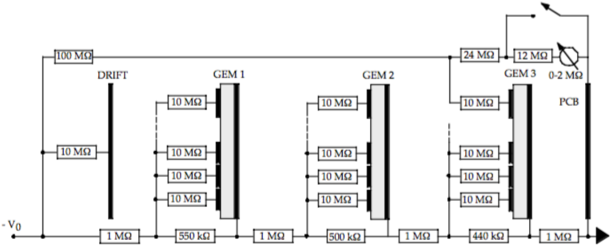
COMPASS: GEM based tracking chambers

- Segmented GEMs in order to reduce the released energy in case of a discharge



Adopted from [10].

- Asymmetric voltage settings: The GEM gain decreases by $\sim 20\,\%$ for each GEM from GEM1 to GEM3
- Pioneered the mass production and corresponding quality assurance of GEM foils



Adopted from [10].

GEMs performance studies: The ALICE TPC Upgrade

The ALICE TPC Upgrade

Motivation: Taking data in LHC Run 3

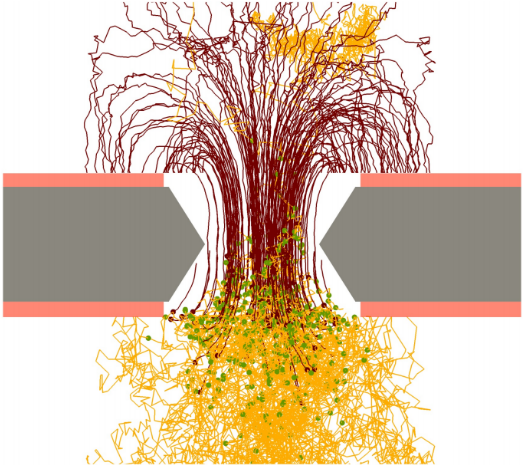
- Increased rate of $\mathrm{Pb}-\mathrm{Pb}$ collisions of up to 50 kHz ($\rightarrow$ 20 μs)
- On average 5 events piled up inside the TPC

$\Rightarrow$ **New readout chambers which allow continuous readout are needed**

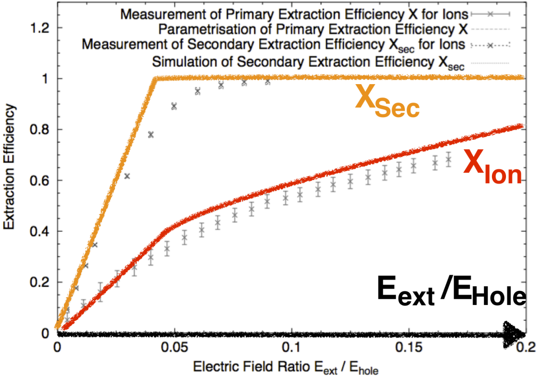
Requirements on the GEM stacks of the new chambers:

- Provide an IBF of less than 1% in order to keep the space charges in the TPC at a tolerable level
- Preserve the momentum and $\mathrm{d}\epsilon/\mathrm{dx}$ resolution of the old chambers ($\frac{\sigma_\epsilon}{\epsilon_{^{55}\mathrm{Fe}}} \leq 12\%$)
- Stable operation at LHC Run 3 conditions

IBF: Intrinsic suppression in a GEM & suppression in a stack



Adopted from [7].



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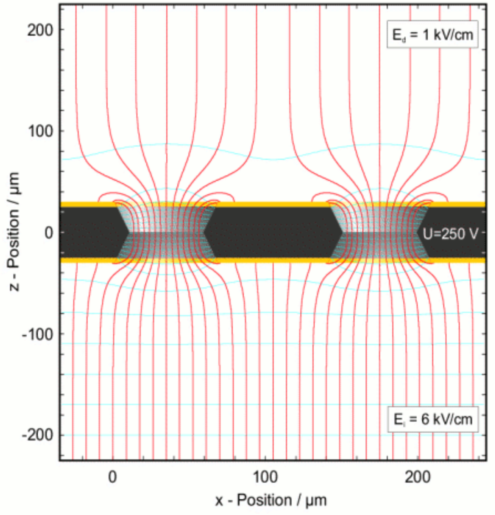
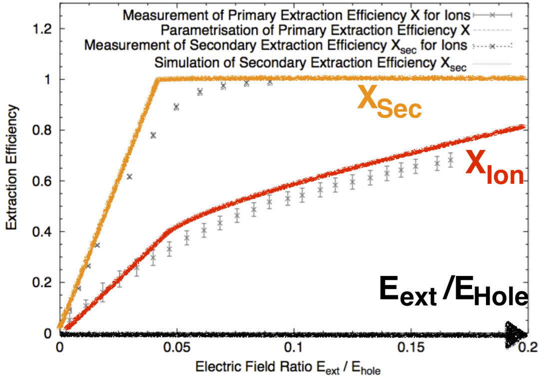




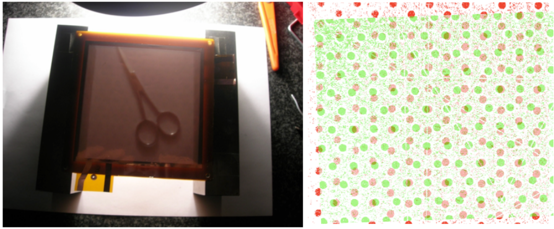
Adopted from [5].

Optimising the IBF

- Low gain in GEM1
- Trap ions from GEM foils with high gain in the transfer regions

→ Maximal misalignment between GEM foils

→ Specially tuned voltage settings



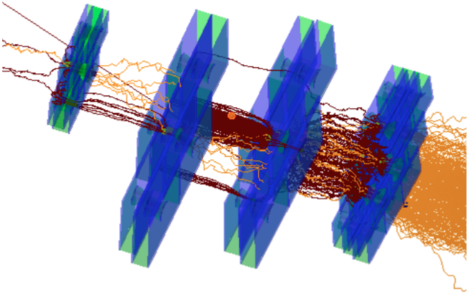
90° relative to the other foil

No rotation of the two foils

Adopted from [8].

Optimising the IBF

ΔU_{GEM1}	ΔU_{GEM2}	ΔU_{GEM3}	ΔU_{GEM4}	E_{D}	E_{T1}	E_{T2}	E_{T3}	E_{Ind}
270 V	230 V	288 V	359 V	$0.4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$0.1\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$



ALICE TPC GEM stacks:

- Quadruple GEM stacks
- Position 1 & 4: Standard GEMs
- Position 2 & 3: Large pitch (280 µm) GEMs
- Each GEM mask rotated by 90 °

Measuring IBF and local energy resolution

IBF & effective gain measurement

- Irradiate a detector with a source (all voltages in the GEM stack at zero)
- Measure the current on the cathode (I_{Primary}) and on the top side of GEM1

$\rightarrow$ Primary ionisation

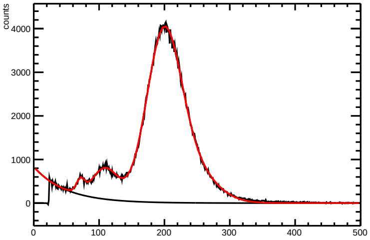
- Apply desired voltage to the stack
- Current measurement on cathode (I_{C}) and anode (I_{A})

$\rightarrow$ $G_{\mathrm{Eff}} = I_{\mathrm{A}}/I_{\mathrm{Primary}}$, $\mathrm{IBF} = I_{\mathrm{C}}/I_{\mathrm{Primary}}$

If e.g. a $^{55}\mathrm{Fe}$ is used, the I_{Primary} can be compared to the expected primary ionisations

Energy resolution

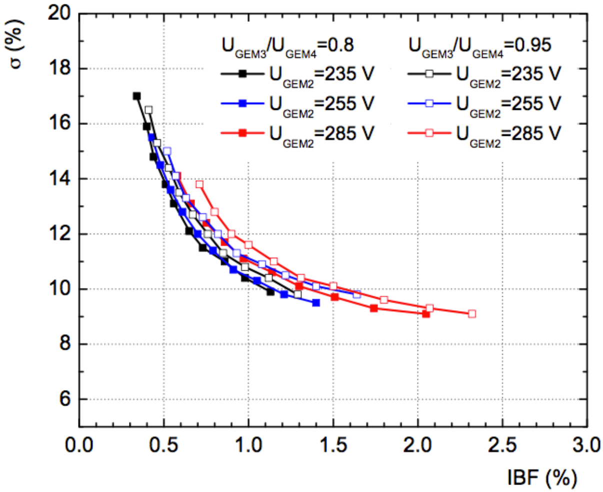
- Set desired voltage settings
- Record a pulse-height spectrum from the signals on the anode plane



Performance: Energy resolution vs IBF

- Quadruple GEM stacks (S-LP-LP-S)
- Done with small prototypes (10 cm × 10 cm GEMs)
- $225\,\mathrm{V} \leq \Delta U_{\mathrm{GEM1}} \leq 315\,\mathrm{V}$, keeping the gain at 2000
- E_{T1} & $E_{\mathrm{Ind}} = 4\,\mathrm{kV\,cm^{-1}}$, $E_{\mathrm{T2}} = 2\,\mathrm{kV\,cm^{-1}}$, $E_{\mathrm{T3}} = 0.1\,\mathrm{kV\,cm^{-1}}$

⇒ **Optimisation of energy resolution and IBF are competing effects**



Adopted from [7].

Discharge studies

Studies with small prototypes

- Studies of single- or more GEMs
- Studies of the quadruple system with the baseline high voltage settings
- Different α sources are used

Studies with real chambers/large prototypes

- SPS beam-time – Particle showers produced by a pion beam impinging on iron blocks
- Chamber qualification tests with high rate X-rays illuminating the whole chambers

Results

- Small prototype's with baseline HV settings: Less than 1.5×10^{-10} discharges per α
- SPS beam-time: $(6 \pm 4) \times 10^{-12}$ discharges per incoming hadrons
- Comparing to 5×10^{-11} particles crossing a GEM stack (on average) during 1 month of lead-lead data taking at 50 kHz

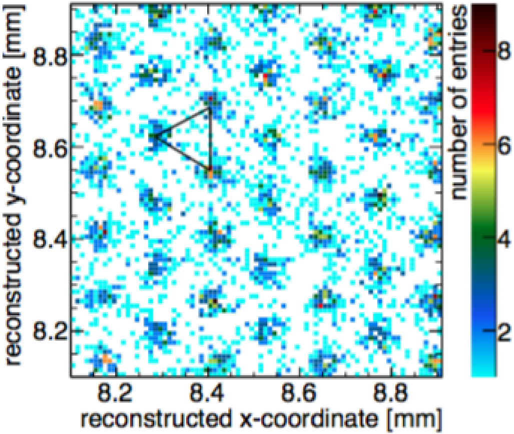
GEMs performance – Other studies and Experiments

A GEM based TPC with pixel readout (ILC group @ Bonn)

Experimental set-up:

- TPC prototype with ~30 cm drift length
- Triple GEM stack
- Readout: A TimePix ASIC with 256×256 pixels with 55 μm pitch

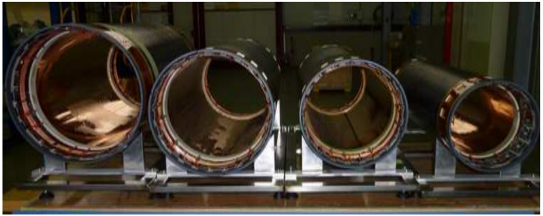
⇒ In the limit of zero diffusion, the single-point resolution is limited by $140\,\mu m/\sqrt{12}$

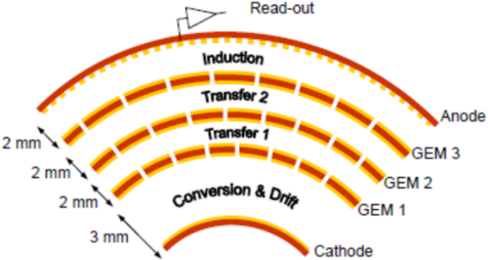


Adopted from [9].

The KLOE-2 inner tracker: A cylindrical GEM detector

- Located at DAΦNE at Frascati, Italy
- Four layers of cylindrical GEM detectors with a triple GEM stack each
- Material budget $< 2\,\% X_0$
- Operated in a 0.5 T magnetic field
- $\sigma_{r\Phi} \sim 200\,\mu\text{m}$ and $\sigma_z \sim 500\,\mu\text{m}$





Adopted from [12].

Summary

- In the last (20) years, the production process of GEMs matured enough to allow the production of many GEMs for small and large prototype R&D
- GEMs are nowadays used in many detectors and foreseen for upgrades of excising detectors (ALICE, CMS)
  (Many detectors and technologies haven't been covered: CMS Muon tracker upgrade, LHCb GEM chambers, X-Ray detection, Thick GEMs, ...)
- The free parameters of a GEM stack allow to tune the performance of a stack to a quite wide range of requirements
- E.g. allowing to use GEM stacks as gas amplification stage in detectors for tracking and PID

Backup

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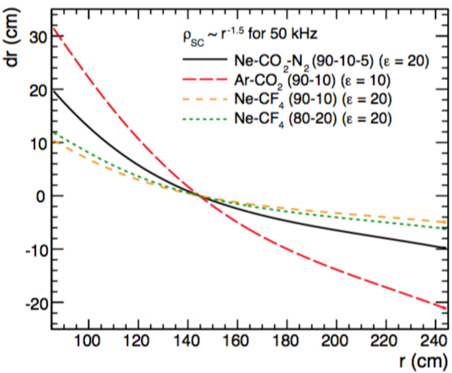
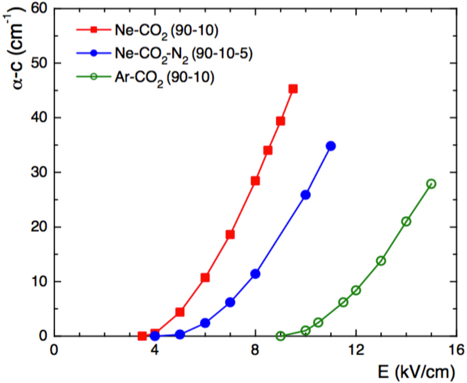
Gas choice





- High ion drift velocity ⇒ **Ne**
- Admixtures of $\mathrm{CO_2}$ as well as $\mathrm{CF_4}$ perform similar in terms of r and $r\phi$ distortions
- The TPC (and the gas system) is not validated for $\mathrm{CF_4}$ ⇒ **Ne-CO$_2$** (90-10)
- Gas amplification in $\mathrm{Ne\text{-}CO_2}$ starts around $4\,\mathrm{kV\,cm^{-1}}$ ⇒ **Ne-CO$_2$-N$_2$** (90-10-5)